Time varying gain (TVG) measurements of a multibeam echo sounder for applications to quantitative acoustics

Dezhang Chu
Woods Hole Oceanographic Institution
Woods Hole, MA 02543, USA

Lawrence C. Hufnagle, Jr.
NOAA-NMFS, Northwest Fisheries Science Center
Seattle, WA 98112-2097, USA

Abstract- **Protocols of calibration procedures of a multibeam echo sounder have been suggested previously [Foote *et al*., 2005, J. Acoust. Am.** 117: **2013-2027], in which the time-varying-gain (TVG) of the multibeam system was assumed to follow the nominal system settings and was not investigated thoroughly. In the current study, the influence of the measured TVGs on system performance was investigated quantitatively. Specifically, measured TVGs were compared to those derived from the nominal system settings for the Simrad SM20 90-kHz multibeam echo sounder (formerly the SM2000 90-kHz),. It was found that for resolved targets, the difference between the theoretically predicted TVG and the measured TVG averaged over all 128 beams was less than 25% for ranges greater than 8 m, equivalent to about 1.0 dB uncertainty in target strength estimates. For unresolved targets, the TVG error is approximately 8 dB at a range of 20 m, resulting in a possible change hy a factor of 6 in abundance estimates. For ranges greater than 120 m, the error reduces to within 1.0 dB, corresponding to about a 25% error in abundance estimate.**

I. INTRODUCTION

During the past decade, multibeam sonars have been increasingly used for target detection, tracking, and behavioral studies in mid-water fisheries acoustic surveys [1]-[4]. Compared to a single beam or split-beam system, a multibeam acoustic system is able to provide much larger volume coverage while maintaining a required spatial resolution. It is thus capable of detecting those fish that would not be detected by a narrow beam sonar due to avoidance. In addition, it can resolve multiple targets located at the same range simultaneously when the targets are separated larger than the angular resolution of the multibeam sonar.

The quantitative application of multibeam sonars to fish stock assessment in acoustic surveys requires that the systems be calibrated. Calibration of a multibeam acoustic system is a challenging task due to the inherent complexity of the system and has been studied in a number of publications [5]-[8]. Protocols of calibrating multibeam sonars in an indoor tank and a seawell were proposed [9] and examples of some commonly used multibeam systems including the Simrad SM2000 90 kHz, SM2000 200-kHz, and Reson 8101 were presented in the paper. It was found that the uncertainties in calibrating a multibeam sonar could be a few decibels (dB) in seawell calibration and less than 1 dB in an indoor tank calibration. In all of the reported calibration studies involving multibeam sonars [5-9], the time varying gain (TVG) was assumed to be inversely proportional to the transmission loss and has not been studied systematically. For many of the multibeam sonar applications, such as seafloor bathymetry mapping [10], target detection and tracking [11], and fish behavior studies [2], [3], [12], the relative echo levels are generally more important than the absolute acoustic backscattering levels, hence an accurate TVG calibration is not a necessity. However, for quantitative applications of multibeam sonars in fisheries acoustics, the estimation of abundance or numeric density of fish in water column over a range from tens of meters to hundreds of meters requires accurate characterization or calibration of the system TVG.

In this paper, we will investigate the influence of a non-ideal TVG of a multibeam sonar on target strength measurements and abundance estimates in fisheries applications.

II. METHOD

We begin with the well known sonar equation [13]. For backscattering from a resolved target, the received echo excess, *EE*, for an active sound system can be expressed as:

$$EE = SL - 2TL + TS + DI - NL \qquad (1)$$

where *SL* is the source level, *TL* is the one way transmission loss including the spherical spreading and the absorption, *TS* is the target strength, *DI* is the sonar directivity index, and *NL* is the ambient noise level.

For unresolved targets, the corresponding *EE* has a slightly different form:

$$EE = SL - 2TL + S_v + \Psi - NL \qquad (2)$$

where S_v is the volume backscattering strength, which is the logarithmic equivalence of the volume backscattering coefficient $10\log_{10} s_v$. Ψ is the logarithmic form of the equivalent beam angle defined as the integration of the beampattern over the entire solid angle space:

$$\Psi = 10\log_{10}\int_{\Omega} b^2(\theta,\varphi)\, d\Omega \qquad (3)$$

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The quantities of Ψ and DI can be determined by calibration with the method of standard target [5]-[9], [14] via the directly measured echo level $EL=EE+NL$. In both (1) and (2), the acoustic system is assumed to have been calibrated and that the fixed system gain associated with the electronics is unity. For most sonar systems including multibeam sonars, the transmission loss (TL) is compensated for by applying a time-varying-gain (TVG) internally. Ideally, the TVG follows the expectation of the theoretical acoustic transmission loss:

$$TL = 20\log_{10} r + \alpha r \qquad (4)$$

for resolved targets used in (1) and

$$TL = 10\log_{10} r + \alpha r \qquad (5)$$

for unresolved targets used in (2), where r is range in meters and α is the absorption coefficient and has a dimension of dB/m. In practice, uncertainties such as crosstalk between channels distort the TVG from those given by (4) and (5). The empirical determination of the actual TVG using the standard target method is very difficult since the TVG will need to be applied for ranges up to hundreds of meters. A standard target cannot be placed at those ranges with satisfactory spatial accuracy.

To overcome such difficulties in determining the actual TVG, we used ambient noise as equivalent acoustic source by setting the transmit output power to zero. With the assumption that the ambient noise is statistically stationary, (i.e. invariant over time) we recorded the time series with specified TVG settings. If the noise is indeed stationary, the recorded voltages should provide an accuracy measure of the actual system TVG. Calculated TVG was based on the system settings recorded in the data header file. By comparing the measured TVG to the calculated TVG, we were able to assess the accuracy of the TVG settings.for target strength and abundance estimates of marine organisms as well as infer the contribution of TVG deviations to uncertainty for quantitative sonar applications.

III. Results and Discussions

We used a Simrad SM20 90-kHz for this study. This system consists of 80 transducer channels and nominally forms 128 beams spanning an angular sector of 90 degree. A more detailed description of the sonar system can be found in reference [9].

As described in the previous section, there are two types of applications: resolved and unresolved targets, for which the corresponding sonar equations are given by (1) and (2), respectively. Since the transmit power was set to zero, the resolved and unresolved targets applications mentioned in the rest of the paper refer to the acoustic sources that contribute to the ambient noise.

A. *Resolved Targets*

The results presented in this sub-section address the outputs when (1) is used to emulate the situation for target strength measurements, where the TVG setting given by (4) is used, i.e. $20\log_{10} r$, to compensate the TL from a resolved echo.

Figure 1 shows the results of the measured TVG averaged over 128 beams with each beam averaged over 50 pings. The absorption coefficient was obtained from the header file of the recorded data, $\alpha = 15$ dB/km. Note that the TVG flattens out at ranges larger than 39.5 m to reach a preset value of about 40 dB.

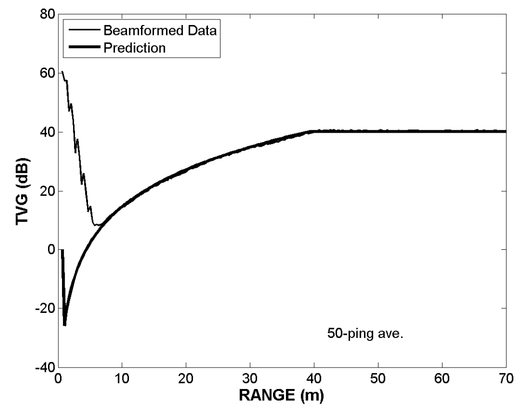

Figure 1. The averaged Time-Varying-Gain (TVG) as a function of range with sonar settings set to detect resolved targets. The average was taken over 50 pings and 128 beams. The thin line is the measured TVG while the thick line is the theoretical prediction using the parameters recorded in the data header file.

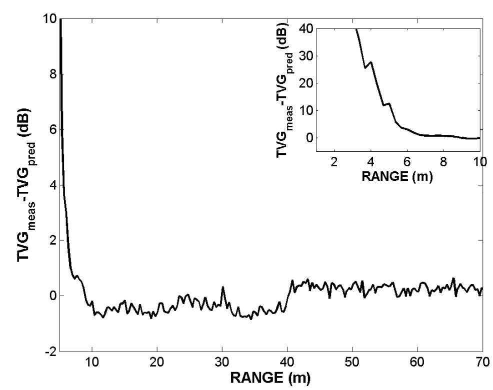

Figure 2. Difference between the measured TVG and the theoretically predicted TVG based on the system settings. The insert is for ranges less than 10 meters.

The measured TVG and the theoretical curves are nearly identical at ranges greater than 8 m. The difference between the curves is shown in Fig. 2, where the inset is for ranges smaller than 10 m. For this particular multibeam system, the Simrad SM20 90-kHz, the far field range is approximately 20 m [9]. Hence, for farfield applications as assumed in most fisheries acoustics, the range-dependent deviation is less than 1.0 dB, or less than a 25% error ($\left|1-10^{1/10}\right|$) in target strength estimate. A larger difference towards the beginning of the TVG curve is observed, reaching 40 dB at about 3.5 m (inset). Even without applying any beamforming operations, the raw time series recorded from each of the 80 receiver channels (not shown) follows almost exactly the same curve shown in Fig. 1, indicating that the difference between two TVGs at the beginning of the time series is not due to near field. This large difference is likely associated with the (electronic) system response of the multibeam sonar. According to the documentation provided by the manufacturer [15], the TVG is applied in the following way:

$$\mathrm{TVG} = \beta \log_{10} \begin{cases} 1, & r < 1 \\ r, & 1 \le r < r_c \\ 1, & r \ge r \end{cases} + \begin{cases} 0 \\ 0 \\ \mathrm{TVG}_{\max} \end{cases}, \quad (6)$$

where $\beta = 20$ for resolved echoes, $\mathrm{TVG}_{\max}$ is set to 40 dB and r_c is the range where the TVG reaches the $\mathrm{TVG}_{\max}$. For this particular case $r_c = 39.5$ m.

The larger signal in the near range is possibly due to channel interference or crosstalk and is not well understood at this point. Since it does not affect any farfield measurements, i.e. greater than 20 m for this system, the large difference between the measured and theoretical TVG curves can be ignored.

In addition to the averaged TVG curve shown in Fig. 1, the variability of TVG between individual beams can also affect the quantitative application of multibeam sonar in fisheries acoustics. Figure 3 is a 2D map of the measured TVGs for all 128 beams, where inter-beam variability can be identified visually. To get a quantitative description of this TVG variability, the standard deviation (thick line) and the difference between the maximum and minimum acoustic intensities (thin line) across among all 128 beams, normalized by the mean TVG averaged over 128 beams and 50 pings, are plotted as a function of range (Fig. 4).

The two quantities that characterize the inter-beam fluctuations show that the overall normalized maximum difference among the beams is much larger (~1.5) than the standard deviation (~0.25). The relative difference of 0.25 in a linear scale corresponds to a deviation of about 25% or about 1 dB in target strength estimate while the maximum possible deviation is 1.5 times that of the actual target strength, or about 1.8 dB.

B. Unresolved Targets

For unresolved targets, $\beta = 10$ in (6) and the TVG increases much slower than that for the resolved target case. As previously, the measured TVG is again averaged over 128 beams with each beam averaged over 50 pings (Fig. 5). The absorption coefficient is still $\alpha = 15$ dB/m. Note that this time

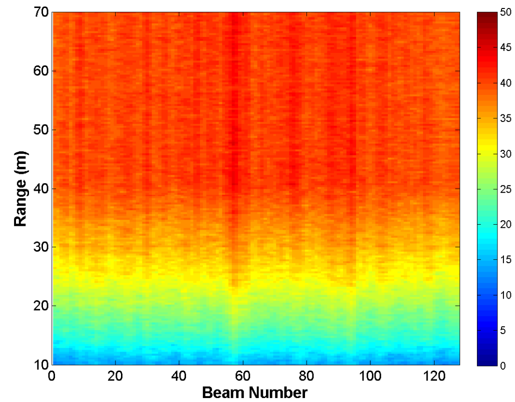

Figure 3. The TVG as a function of beam number and the range. The color scale is in dB.

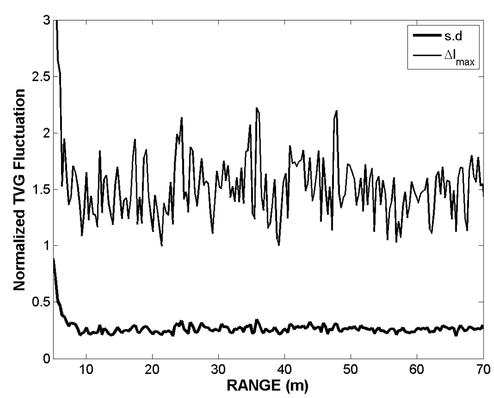

Figure 4. The standard deviation (thick line) and the maximum difference between the largest and smallest acoustic intensities (thin line) across among all 128 beams as a function of range. The quantities are normalized by the mean TVG averaged over 128 beams and 50 pings at each range sample point.

the TVG flattens out (~40 dB) at a range of about 280 m, a distance much greater than that for the resolved target case.

The measured TVG curve follows the theoretical curve reasonably well for ranges greater than 70 m. The difference between the curves is plotted in Fig. 6, where the inset is for range smaller than 30 m. Compared to the case for resolved targets, the difference is much larger, about 8 dB at 20 m, or a factor of more than 6 for a fish abundance estimate. The difference reduces to less than 1 dB, or less than a 25% error in abundance estimates for ranges greater than 120 m. Since fish schools are commonly observed within tens of meters to a couple of hundred meters in water column, without taking into account the TVG deviation, the accuracy in abundance estimate using this sonar could be affected significantly, depending on the ranges at which the fish schools are located.

In addition, similar to the resolved target case, the big difference towards the beginning of the TVG curve is still observed, reaching 25 dB at 5 m (inset). As stated previously, the far field is in the range $r > 20$ m, hence the large difference between the measured and theoretical TVGs at smaller range can be ignored.

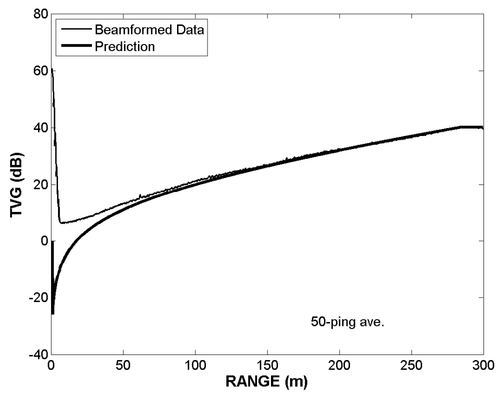

Figure 5. Comparison of predicted and observed TVG as a function of range with sonar settings set to detect unresolved targets. The average was taken over 50 pings and 128 beams.

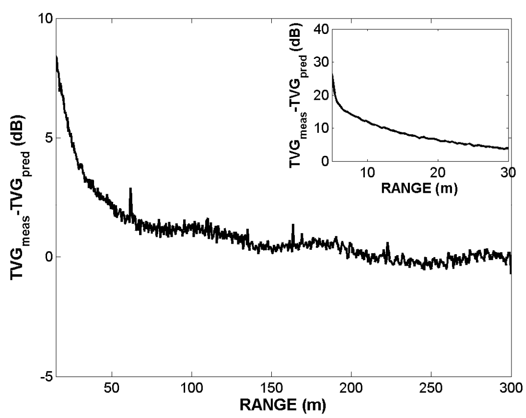

Figure 6. Difference between the measured TVG (TVG_{meas}) and that from the theoretical prediction (TVG_{pred}).

Figures 7 and 8 respectively show the corresponding 2D map and the fluctuation characteristics of the TVG function for unresolved targets. In contrast to Figs. 3 and 4 where the trend of TVG changes smoothly with range, in Figs. 7 and 8 there is a sudden change in the inter-beam fluctuations around $r = 135$ m. The overall levels of the normalized standard deviation and the maximum intensity difference for $r \leq 135$ m are similar to those in the resolved target case. The possible errors in abundance estimate are 1.5 times the actual abundances for the extreme case and 25% when the normalized fluctuation is less than one standard deviation. For $r \geq 135$ m, the fluctuations are reduced to about half of their values, hence the error in abundance estimates are as well. The reason for this sudden change is not very clear.

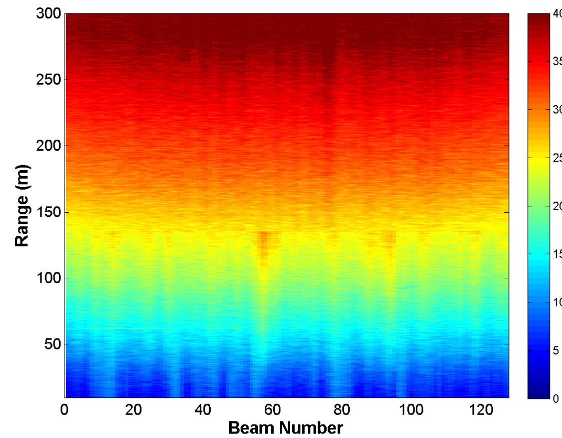

Figure 7. The TVG as a function of beam number and the range. The color scale is in dB.

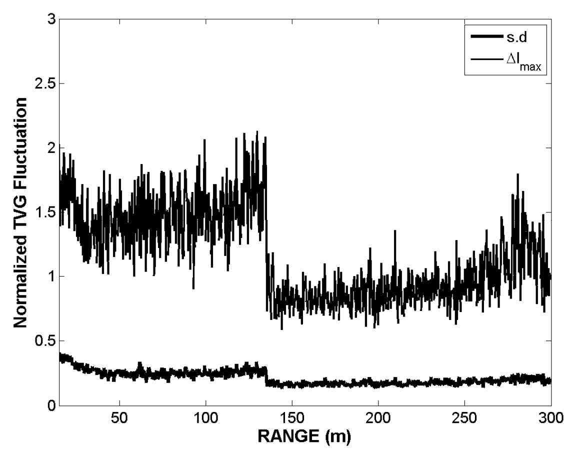

Figure 8. The standard deviation (thick line) and the maximum difference between the largest and smallest acoustic intensities (thin line) across among all 128 beams as a function of range. The quantities are normalized by the mean TVG averaged over 128 beams and 50 pings at each range sample point.

IV. Conclusions

We have investigated the influence of the time varying gain (TVG) of a multibeam sonar on its quantitative application. With zero transmit power, the ambient noise was recorded to emulate the actual TVG. The inconsistency between the measured TVG and the theoretically predicted TVG has been analyzed in this paper. The errors for two types of operations, cases involving resolved and unresolved targets, have been examined. The errors for resolved targets are relatively smaller than those for the unresolved targets. There is about 0.5 dB error in target strength measurements but as much as 6 times error in abundance estimate at the range near 20 m. In the extreme case, inter-beam fluctuation or variability could lead to about 1.8 dB error in target strength estimate and 1.5 times error in abundance estimate.

The analysis presented in this paper reveals the importance of obtaining an accurate TVG in measuring target strength and estimating abundance in fisheries applications with multibeam sonars.

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REFERENCES

[1] F. Gerlotto, M. Soria, and P. Fréon, “From two dimensions to three: the use of multibeam sonar for a new approach in fisheries acoustics,” *Can. J. Fish. Aquat. Sci.* vol. 56, 6-12, 1999.

[2] O.A. Misund and A. Aglen, “Swimming behavior of fish schools in the North Sea during acoustic surveying and pelagic trawl sampling,” *ICES J. mar. Sci.* vol. 49, 325-334, 1992.

[3] M. T. Hafsteinsson, and O. A. Misund, “Recording the migration behavior of fish schools by multibeam sonar during conventional acoustic surveys,” *ICES J. mar. Sci*. vol. 52, 915-924, 1995.

[4] L. Mayer, Y. Li, and G. Melvin, “3D visualization for pelagic fisheries research and assessment,” *ICES J. mar. Sci*. vol. 59, 216-225, 2002.

[5] D. Chu, K. C. Baldwin, K. G. Foote, Y. Li, L. A. Mayer, and G. D. Melvin, "Multibeam sonar calibration: target localization in azimuth," *Proc. MTS/IEEE* Oceans 2001, 2506–2510, 2001.

[6] D. Chu, K. G. Foote, and L. C. Hufnagle, Jr., “Measurement of ultibeam sonar directivity patterns,” *Proc. MTS/IEEE* Oceans 2002, 1411-1414, 2002.

[7] D. Chu, K. G. Foote, L. C. Hufnagle, Jr., K. C. Baldwin, L. A. Mayer, and A. McLeod, “Calibrating a 90-kHz multibeam sonar,” *Proc. MTS/IEEE* Oceans 2003,1633-1636, 2003.

[8] N. A. Cochrane, Y. Li, and G. D. Melvin, “Quantification of a multibeam sonar for fisheries assessment applications,” *J. Acoust. Soc. Am.* vol. 114, 745-758, 2003.

[9] K. G. Foote, D. Chu, K. C. Baldwin, L. A. Mayer, A. McLeod, L. C. Hufnagle, Jr., J. M. Jech, and W. Michaels, “Protocols for calibrating multibeam sonar,” *J. Acoust. Soc. Am*. vol. 117, 2013-2027, 2005.

[10] L. Mayer and C. de Moustier, “Seafloor mapping and 3-D visualization: An integration of technologies providing new insights into seafloor processes,”*J. Acoust. Soc. Am*. vol. 107, 2771, 2000.

[11] .Benoit-Bird and W. Au, “Hawaiian spinner dolphins aggregate midwater food resources through cooperative foraging,” *J. Acoust. Soc. Am.* Vol.114, 2300, 2003.

[12] O. A. Misund, “Dynamics of moving masses: variability in packing density, shape, and size among herring, sprat and saithe schools,” *ICES J. mar. Sci.* vol. 50, 145-160, 1993.

[13] R. J. Urick, *Principles of underwater sound*, 3rd ed. McGraw-Hill, New York, 1983.

[14] K. G. Foote, H. P. Knudsen, G. Vestnes, D. N. MacLennan, and E. J. Simmonds, “Calibration of acoustic instruments for fish density estimation: a practical guide,” *ICES Coop. Res. Rep.* (144), 69 pp, 1987.

[15] Private communication.